

Reducing the Wildland Fire Threat to Homes: Where and How Much?¹

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Abstract

Understanding how ignitions occur is critical for effectively mitigating home fire losses during wildland fires. The threat of life and property losses during wildland fires is a significant issue for Federal, State, and local agencies that have responsibilities involving homes within and adjacent to wildlands. Agencies have shifted attention to communities adjacent to wildlands through pre-suppression and suppression activities. Research for the Structure Ignition Assessment Model (SIAM) that includes modeling, experiments, and case studies indicates that effective residential fire loss mitigation must focus on the home and its immediate surroundings. This has significant implications for agency policy and specific activities such as hazard mapping and fuel management.

The threat of life and property losses during wildland fires is a significant issue for Federal, State, and local fire and planning agencies who must consider residential development within and adjacent to wildlands. The 1995 USDA Forest Service *Strategic Assessment of Fire Management* (USDA Forest Service 1995) lists five principal fire management issues. One of those issues is the “loss of lives, property, and resources associated with fire in the wildland/urban interface” (p. 3). The report further identifies “the management of fire and fuels in the wildland/urban interface” as a topic for further assessment. Because this is more than a Forest Service issue, the National Wildland/Urban Interface Fire Protection Program, a multi-agency endeavor, has been established for over a decade and is sponsored by the Department of Interior land management agencies, the USDA Forest Service, the National Association of State Foresters, and the National Fire Protection Association. This program also has an advisory committee associated with the multi-agency National Wildfire Coordinating Group. These examples indicate that the wildland fire threat to homes significantly influences fire management policies and suggests that this issue has significant economic impacts through management activities, direct property losses, and associated tort claims.

The wildland fire threat to homes is commonly termed the wildland-urban interface (W-UI) fire problem. This and similar terms (e.g., wildland-urban intermix) refer to an area or location where a wildland fire can potentially ignite Homes. A senior physicist at the Stanford Research Institute, C.P. Butler (1974), coined the term “urban-wildland interface” and described this fire problem:

In its simplest terms, the fire interface is any point where the fuel feeding a wildfire changes from natural (wildland) fuel to man-made (urban) fuel. ...For this to happen, wildland fire must be close enough for its flying brands or flames to contact the flammable parts of the structure (p. 3).

In his definition, Butler provides important references to the characteristics of this problem. He identifies homes (“urban”) as potential fuel and indicates that the distance between the wildland fire and the home (“close enough”) is an important factor for structure ignition. How close the fire is to a home relates to how much heat the structure will receive.

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These two factors, the homes and fire proximity, represent the fuel and heat “sides” of the fire triangle, respectively. The fire triangle—fuel, heat, and oxygen—represents the critical factors for combustion. Fires burn and ignitions occur only if a sufficient supply of each factor is present. By characterizing the home as fuel and the heat from flames and firebrands, we can describe a home’s ignitability. An understanding of home ignitability provides a basis for reducing potential W-UI fire losses in a more effective and efficient manner than current approaches.

Ignition and Fire Spread are a Local Process

Fire spreads as a continually propagating process, not as a moving mass. Unlike a flash flood or an avalanche where a mass engulfs objects in its path, fire spreads because the locations along the path meet the requirements for combustion. For example, C.P. Butler (1974) provides an account from 1848 by Henry Lewis about pioneers being caught on the Great Plains during a fire:

When the emigrants are surprised by a prairie fire, they mow down the grass on a patch of land large enough for the wagon, horse, etc., to stand on. They then pile up the grass and light it. The same wind, which is sweeping the original fire toward them, now drives the second fire away from them. Thus, although they are surrounded by a sea of flames, they are relatively safe. Where the grass is cut, the fire has no fuel and goes no further. In this way, experienced people may escape a terrible fate (p. 1-2).

It is important to note that the complete success of this technique also relies on their wagons and other goods not igniting and burning from firebrands. This account describes a situation that has similarities with the W-UI fire problem.

A wildland fire does not spread to homes unless the homes meet the fuel and heat requirements sufficient for ignition and continued combustion. In the prairie fire situation, sufficient fuel was removed (by their escape fire) adjacent to the wagons to prevent burning (and injury) and the wagons were ignition resistant enough to not ignite and burn from firebrands. Similarly, the flammables adjacent to a home can be managed with the home’s materials and design chosen to minimize potential firebrand ignitions. This can occur regardless of how intensely or fast spreading other fires are burning. Reducing W-UI fire losses must involve a reduction in the flammability of the home (fuel) in relation to its potential severe-case exposure from flames and firebrands (heat). The essential question remains as to how much reduction in flammables (e.g., how much vegetative fuel clearance) must be done relative to the home fuel characteristics to significantly reduce the potential home losses associated with wildland fires.

Insights for Reducing Ignitions from Flames

Recent research provides insights for determining the vegetation clearance required for reducing home ignitions. Structure ignition modeling, fire experiments, and W-UI fire case studies provide a consistent indication of the fuel and heat required for home ignitions.

The Structure Ignition Assessment Model (SIAM) (Cohen 1995) assesses the potential ignitability of a structure related to the W-UI fire context. SIAM calculates the amount of heat transferred to a structure from a flame source on the basis of the flame characteristics and the flame distance from a structure. Then, given this thermal exposure, SIAM calculates the amount of time required for the occurrence of wood ignition and flaming (Tran and others 1992). On the basis of severe-case assumptions of flame radiation and exposure time, SIAM calculations indicate that large wildland flame fronts (e.g., forest crown fires) will not ignite wood surfaces (e.g., the typical variety of exterior wood walls) at distances greater than 40 meters (Cohen and Butler [In press]). For example, the incident radiant heat flux, the amount of radiant heat a wall would receive from flames, depends on its distance from the fire. That is, the rate of radiant energy

per unit wall area decreases as the distance increases (*fig. 1*). In addition, the time required for a wood wall to ignite depends on its distance from a flame front of the given height and width (*fig. 1*). But the flame's burning time compared to the required ignition time is important. If at some distance the fire front produces a heat flux sufficient to ignite a wood wall, but the flaming duration is less than that required for ignition, then ignition will not occur. At a distance of 40 meters, the radiant heat flux is less than 20 kilowatts per square meter, which corresponds to a minimum ignition time of greater than 10 minutes (*fig. 1*). Crown fire experiments in forests and shrublands indicate that the burning duration of these large flames is on the order of 1 minute at a specific location.³ This is because these wildland fires depend on the rapid consumption of the fine dead and live vegetation (e.g., forest crown fires).

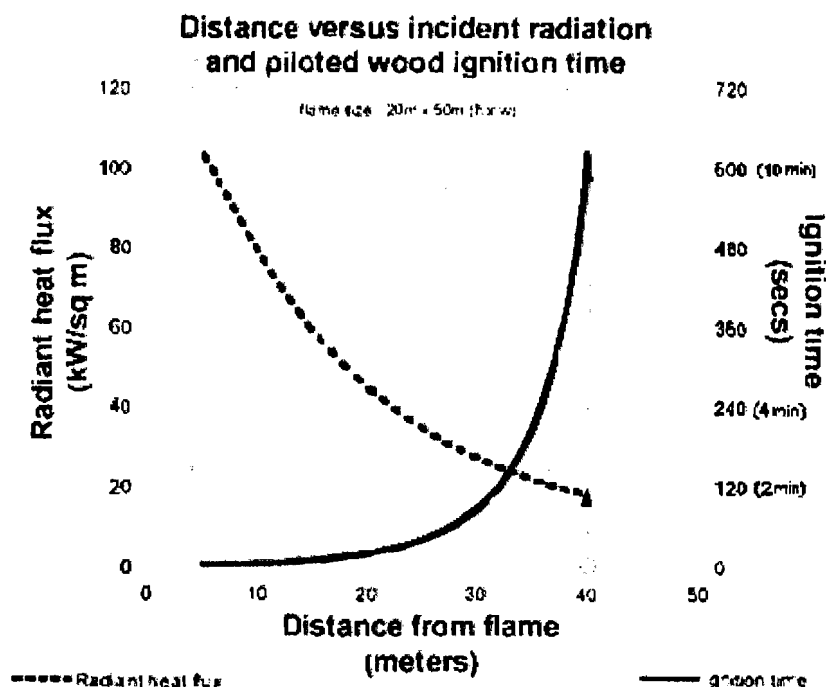


Figure 1

SIAM calculates the incident radiant heat flux (energy/unit-area/time reaching a surface) and the minimum time for piloted ignition (ignition with a small ignition flame or spark) as a function of distance for the given flame size. The flame is assumed to be a uniform, parallel plane, black body emitter.

Experimental fire studies associated with the International Crown Fire Modeling Experiment (Alexander and others 1998) generally concur with the SIAM calculations. Data were obtained from instrumented wall sections that were placed 10 meters from the forest edge of the crown fire burn plots. Comparisons between SIAM calculations and the observed heat flux data indicate that SIAM overestimates the amount of heat received.⁴ For example, the SIAM calculated potential radiant heat flux for an experimental crown fire was 69 kW/ sq meter as compared to the measured maximum of 46 kW/sq meter. This is expected since SIAM assumes a uniform and constant heat source and flames are not uniform and constant. Thus, the SIAM calculations for an actual flame front represent a severe-case estimate of the heat received and the potential for ignition. The SIAM distances represent an upper estimate of the separation required to prevent flame ignitions (*fig. 1*).

Past fire case studies also generally concur with SIAM estimates and the crown fire observations. Analyses of southern California home losses done by the Stanford Research Institute for the 1961 Belair-Brentwood Fire (Howard and others 1973) and by the University of California, Berkeley, for the 1990 Painted Cave Fire (Foote and Gilless 1996) are consistent with SIAM estimates and the experimental crown fire data. Given nonflammable roofs, Stanford Research

³ Unpublished data on file, Rocky Mountain Research Station, Fire Sciences Laboratory) Missoula, Montana.

⁴ Unpublished data on file, Rocky Mountain Research Station, Fire Sciences Laboratory, Missoula, Montana.

Institute (Howard and others 1973) found a 95 percent survival with a clearance of 10 to 18 meters, and Foote and Gilles (1996) at Berkeley found 86 percent home survival with a clearance of 10 meters or more.

The results of the diverse analytical methods are congruent and consistently indicate that ignitions from flames occur over relatively short distances—tens of meters not hundreds of meters. The severe-case estimate of SIAM indicates distances of 40 meters or less. Experimental wood walls did not ignite at 10 meters when exposed to experimental crown fires. And, case studies found that vegetation clearance of at least 10 meters was associated with a high occurrence of home survival.

As previously mentioned, firebrands are also a principal W/UI ignition factor. Highly ignitable homes can ignite during wildland fires without fire spreading near the structure. This occurs when firebrands are lofted downwind from fires. The firebrands subsequently collect on and ignite flammable home materials and adjacent flammables. Firebrands that result in ignitions can originate from wildland fires that are at a distance of 1 kilometer or more. For example, during the 1980 Panorama Fire (San Bernardino, California), the initial firebrand ignitions to homes occurred when the wildland fire was burning in low shrubs about 1 kilometer from the neighborhood. During severe W/UI fires, firebrand ignitions are particularly evident for homes with flammable roofs. Often these houses ignite and burn without the surrounding vegetation also burning. This suggests that homes can be more flammable than the surrounding vegetation. For example, during the 1991 fires in Spokane, Washington,⁵ houses with flammable roofs ignited without the adjacent vegetation already burning. Although firebrands may be lofted over considerable distances to ignite homes, a home's materials and design and its adjacent flammables largely determine the firebrand ignition potential.

Research Conclusions

SIAM modeling, crown fire experiments, and W/UI fire case studies show that effective fuel modification for reducing potential W/UI fire losses need only occur within a few tens of meters from a home, not hundreds of meters or more from a home. This research indicates that home losses can be effectively reduced by focusing mitigation efforts on the structure and its immediate surroundings. Those characteristics of a structure's materials and design and the surrounding flammables that determine the potential for a home to ignite during wildland fires (or any fires outside the home) can be referred to as home ignitability.

The evidence suggests that wildland fuel reduction for reducing home losses may be inefficient and ineffective: inefficient because wildland fuel reduction for several 100 meters or more around homes is greater than necessary for reducing ignitions from flames; ineffective because it does not sufficiently reduce firebrand ignitions. To be effective, given no modification of home ignition characteristics, wildland vegetation management would have to significantly reduce firebrand production and potentially extend for several kilometers away from homes.

Management Implications

These research conclusions redefine the W/UI home fire loss problem as a home ignitability issue largely independent of wildland fuel management issues. Consequently, this description has significant implications for the necessary actions and economic considerations for fire agencies.

One aspect of the Forest Service approach to reducing the W/UI fire problem is to determine where the problem is and focus fuel management activities in those areas. *The Strategic Assessment of Fire Management* (USDA Forest Service 1995) states:

⁵Unpublished video data on file, Rock) Mountain Research Station, Fire Sciences Laboratory, Missoula, Montana.

The Forest Service should manage National Forest lands to mitigate hazards and enhance the ability to control fires in the wildland/urban interface. The risk of wildland fire to communities can be lessened by reducing hazards on Forest Service lands adjacent to built-up areas.... Broad-scale assessment processes for the next generation of forest plans should identify high-risk areas related to the wildland/urban interface... The highest risk areas within the United States should be identified and mitigation efforts directed to these locations (p. 20).

It describes a costly, intensive, and extensive W-UI hazard mapping and mitigation effort specifically for reducing home fire losses. As described, this approach is not necessary.

The congruence of research findings from different analytical methods suggests that home ignitability is the principal cause of home losses during wildland fires. Any W-UI home fire loss assessment method that does not account for home ignitability will be critically non-specific to the problem. Thus, to be reliable, land classification and mapping related to potential home loss must assess home ignitability. Home ignitability also dictates that effective mitigating actions focus on the home and its immediate surroundings rather than on extensive wildland fuel management. Because homeowners typically assert their authority for the home and its immediate surroundings, the responsibility for effectively reducing home ignitability can only reside with the property owner rather than wildland agencies.

Mapping Home Loss Potential

The evidence indicates that home ignitions depend on the home materials and design and only those flammables within a few tens of meters of the home (home ignitability). The wildland fuel characteristics beyond the home site have little if any significance to W-UI home fire losses. Thus, the wildland fire threat to homes is better defined by home ignitability, an ignition and combustion consideration, than by the location and behavior of potential wildland fires.

Home ignitability has implications for identifying W-UI fire problem areas and suggests that the geographical implication of the term “wildland-urban interface” as a general area or zone misrepresents the physical nature of the wildland fire threat to homes. The wildland fire threat to homes is not where it happens related to wildlands (a location) but how it happens related to home ignitability (the combustion process). Therefore, to reliably map W-UI home fire loss potential, home ignitability must be the principal mapping characteristic.

Wildland Fuel Hazard Reduction

Extensive wildland vegetation management does not effectively change home ignitability. This should not imply that wildland vegetation management is without a purpose and should not occur for other reasons. However, it does imply the imperative to separate the problem of the wildland fire threat to homes from the problem of ecosystem sustainability due to changes in wildland fuels. For example, a W-UI area could be a high priority for extensive vegetation management because of aesthetics, watershed, erosion, or other values, but not for reducing home ignitability. Vegetation management strategies would likely be different without including the W-UI home fire loss issue. It also suggests that given a low level of home ignitability (reduced wildland fire threat to homes), fire use opportunities for sustaining ecosystems may increase in and around WUI locations.

W-UI Home Loss Responsibility

Home ignitability implies that homeowners have the ultimate responsibility for W-UI home fire loss potential. Because the ignition and flammability

characteristics of a structure and its immediate surroundings determine the home fire loss potential, the home should not be considered a victim of wildland fire, but rather a potential participant in the continuation of the wildland fire. Home ignitability, i.e., the potential for W/UI home fire loss, is the homeowner's choice and responsibility.

However, public and management perceptions may impede homeowners from taking principal responsibility. For example, the Federal Wildland Fire Management, Policy, and Program Review (1995) observes, "There is a widespread misconception by elected officials, agency managers, and the public that wildland/urban interface protection is solely a fire service concern" (p. 23). In the *Journal of Forestry*, Beebe and Omi (1993) concur, stating that, "Public reaction to wildfire suggests that many Americans want competent professionals to manage fire flawlessly, reducing the risks to life, property, and public lands to nil" (p. 24). These statements agree with Bradshaw's (1988) description of the societal roles in the W/UI problem. He observes that homeowners expect that fire protection will be provided by others. Contrary to these expectations for fire protection, the fire services have neither the resources for effectively protecting highly ignitable homes during severe W/UI fires, nor the authority to reduce home ignitability.

An Alternative

Specific to the W/UI fire loss problem, home ignitability ultimately implies the necessity for a change in the relationship between homeowners and the fire services. Instead of all pre-suppression and fire protection responsibilities reading with fire agencies, homeowners should take the principal responsibility for assuring adequately low home ignitability. The fire services become a community partner providing homeowners with technical assistance as well as fire response in a strategy of assisted and managed community self-sufficiency (Cohen and Saveland 1997). For success, this perspective must be shared and implemented equally by homeowners and the fire services.

References

- Alexander, ME; Stocks, B.J. Wotton, B.M.; Flannigan, M.D.; Todd, J.B.; Butler, B.W.; Lanoville, R.A. 1998. **The international crown fire modelling experiment: an overview and progress report.** In: Proceedings of the second symposium on fire and forest meteorology; 1998 January 12-14; Phoenix, AZ. Boston, MA: American Meteorological Society; 20-23.
- Beebe, Grant S.; Omi, Philip N. 1993. **Wildland burning: the perception of risk.** *Journal of Forestry* 91(9): 19-24.
- Bradshaw, William C. 1988. **Fire protection in the urban/wildland interface: who plays what role?** *Fire Technology* 24(3): 195-203.
- Butler, C.P. 1974. **The urban/wildland fire interface.** In: Proceedings of Western states section! Combustion Institute papers, vol. 74, no. 15; 1974 May 6-7; Spokane, WA. Pullman, WA: Washington State University; 1-17.
- Cohen, Jack U. 1995. **Structure ignition assessment model (SIAM).** In: Weise, David R.; Martin, Robert F., technical coordinators. Proceedings of the Biswell symposium: fire issues and solutions in urban interface and wildland ecosystems; 1994 February 15-17; Walnut Creek) CA. Cen. Tech. Rep. PSW-CTR-158. Albany, CA: Pacific Southwest Research Station, Forest Service, U.S. Department of Agriculture; 85-92.
- Cohen, Jack U.; Butler, Bret W. [In press]. **Modeling potential ignitions from flame radiation exposure with implications for wildland/urban interface fire management.** In: Proceedings of the 13th conference on fire and forest meteorology; 1996 October 27-31; Lorne, Victoria, Australia. Fairfield, WA: International Association of Wildland Fire.
- Cohen, Jack; Saveland, Jim. 1997. **Structure ignition assessment can help reduce fire damages in the W/UI.** *Fire Management Notes* 57(4): 19-23.
- Foote, Ethan ID.; Gillies, J. Keith. 1996. **Structural survival.** In: Slaughter, Rodney, ed. California's I-zone. Sacramento, CA: CFESTES; 112-121.
- Howard, Ronald A.; North, U. Warner; Offensend, Fred L.; Smart, Charles N. 1973. **Decision analysis of fire protection strategy for the Santa Monica mountains: an initial assessment.** Menlo Park, CA: Stanford Research Institute; 159 p.

Tran, Hao C.; Cohen, Jack D.; Chase, Richard A. 1992. **Modeling ignition of structures in wildland/ urban interface fires.** In: Proceedings of the 1st international fire and materials conference; 1992 September 24-25; Arlington, VA. London, UK: Inter Science Communications Limited; 253-262.

USDA Forest Service. 1995. **Strategic assessment of fire management in the USDA Forest Service.** 1995 January 13, Washington, DC: U.S. Forest Service, Department of Agriculture; 31 p.

USDI/USDA. 1995. **Federal wildland fire management: policy & review.** 1995 December 18. Washington, DC: Department of the Interior and Department of Agriculture; 45 p.

Warming and Earlier Spring Increases Western U.S. Forest Wildfire Activity

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Western United States forest wildfire activity is widely thought to have increased in recent decades, but surprisingly, the extent of recent changes has never been systematically documented. Nor has it been established to what degree climate may be driving regional changes in wildfire. Much of the public and scientific discussion of changes in western United States wildfire has focused rather on the effects of 19th and 20th century land-use history. We compiled a comprehensive database of large wildfires in western United States forests since 1970 and compared it to hydro-climatic and land-surface data. Here, we show that large wildfire activity increased suddenly and dramatically in the mid-1980s, with higher large-wildfire frequency, longer wildfire durations, and longer wildfire seasons. The greatest increases occurred in mid-elevation, Northern Rockies forests, where land-use histories have relatively little effect on fire risks, and are strongly associated with increased spring and summer temperatures and an earlier spring snowmelt.

Wildfires have consumed increasing areas of western U.S. forests in recent years, and fire-fighting expenditures by federal land management agencies now regularly exceed US\$1 billion/year (1). Hundreds of homes are burned annually by wildfires, and damages to natural resources are sometimes extreme and irreversible. Media reports of recent, very large wildfires (>100,000 ha) burning in western forests have garnered widespread public attention, and a recurrent perception of crisis has galvanized legislative and administrative action (1–3).

Extensive discussions within the fire management and scientific communities and the media seek to explain these phenomena, focusing on either land-use history or climate as primary causes. If increased wildfire risks are driven primarily by land-use history, then ecological restoration and fuels management are potential solutions. However, if increased risks are largely due to changes in climate during recent decades, then restoration and fuels treatments may be relatively ineffective in reversing current wildfire trends (4, 5). Here we investigate 34 years of western United States (“western”) wildfire history together with hydro-climatic data

to determine where the largest increases in wildfire have occurred, and to evaluate how recent climatic trends may have been important causal factors.

Competing explanations: Climate versus management.

Land-use explanations for increased western wildfire note that extensive livestock grazing and increasingly effective fire suppression began in the late 19th and early 20th centuries, reducing the frequency of large surface fires (6–8). Forest re-growth after extensive logging beginning in the late 19th century, combined with an absence of extensive fires, promoted forest structure changes and biomass accumulation which now reduce the effectiveness of fire suppression and increase the size of wildfires and total area burned (3, 5, 9). The effects of land-use history on forest structure and biomass accumulation are, however, highly dependent upon the “natural fire regime” for any particular forest type. For example, the effects of fire exclusion are thought to be profound in forests that previously sustained frequent, low intensity surface fires [e.g., Southwestern ponderosa pine and Sierra Nevada mixed conifer (2, 3, 10, 11)], but of little or no consequence in forests that previously sustained only very infrequent, high severity crown fires (e.g., Northern Rockies lodgepole pine or spruce-fir (1, 5, 12)).

In contrast, climatic explanations posit that increasing variability in moisture conditions (wet/dry oscillations promoting biomass growth, then burning), and/or a trend of increasing drought frequency, and/or warming temperatures, have led to increased wildfire activity (13, 14). Documentary records and proxy reconstructions (primarily from tree rings) of fire history and climate provide evidence that western forest wildfire risks are strongly positively associated with drought concurrent with the summer fire season, and (particularly in ponderosa pine-dominant forests) positively associated to a lesser extent with moist conditions in antecedent years (13–18). Variability in western climate related to the Pacific Decadal Oscillation and intense El Niño/La Niña events in recent decades, along with severe droughts in 2000 and 2002 may have promoted greater forest wildfire risks in areas like the Southwest, where precipitation anomalies are significantly influenced by patterns in Pacific

sea surface temperature (19–22). Although corresponding decadal-scale variations and trends in climate and wildfire have been identified in paleo studies, there is a paucity of evidence for such associations in the twentieth century.

We describe land-use history versus climate as competing explanations, but in fact they may be complementary in some places. In some forest types, past land-uses have probably increased current forest wildfire regimes' sensitivity to climatic variability through effects on the quantity, arrangement, and continuity of fuels. Hence, an increased incidence of large, high-severity fires may be due to a combination of extreme droughts and over-abundant fuels in some forests. Climate, however, may still be the primary driver of forest wildfire risks on interannual to decadal scales. On decadal scales, climatic means and variability shape the character of the vegetation (e.g., species populations and their drought tolerance (23), and biomass (fuel) continuity (24), thus also affecting fire regime responses to shorter term climate variability). On interannual and shorter time scales, climate variability affects the flammability of live and dead forest vegetation. (13–19, 25)

High-quality time series are essential for evaluating wildfire risks, but for various reasons (26), previous works have not rigorously documented changes in large wildfire frequency for western forests. Likewise, detailed fire-climate analyses for the region have not been conducted to evaluate what hydro-climatic variations may be associated with recent increased wildfire activity, and the spatial variations in these patterns.

We compiled a comprehensive time series of 1,166 large (> 400 ha) forest wildfires for 1970–2003 from federal land management units containing 61% of western forested areas (and 80% above 1,370m) (26) (fig. S1). We compared these data with corresponding hydro-climatic and land surface variables (26–34) to address where and why the frequency of large forest wildfire has changed.

Increased forest wildfire activity. We found the incidence of large wildfires in western forests increased in the mid-1980s (Fig. 1) [hereafter, “wildfires” refers to large fire events (>400 ha) within forested areas only (26)]. Subsequently, wildfire frequency was nearly four times the average of 1970–1986, and total area burned by these fires was more than six and a half times its previous level. Interannual variability in wildfire frequency is strongly associated with regional spring and summer temperature (Spearman's correlation of 0.76, $p < 0.001$, $n = 34$). A second-order polynomial fit to the regional temperature signal alone explains 66% of variance in the annual incidence of these fires, with many more wildfires burning in hotter than in cooler years.

The length of the wildfire season also increased in the 1980s (Fig. 1). The average season-length (the time between

the reported first wildfire discovery date and the last wildfire control date) increased by 78 days (64%), comparing 1970–86 to 1987–03. Roughly half that increase was due to earlier ignitions, and half to later control (48% versus 52%, respectively). While later control dates were no doubt partly due to later ignition dates, with the date of the last reported wildfire ignition increasing by 15 days, a substantial increase in the length of time the average wildfire burned also played a role. The average time between discovery and control for a wildfire increased from 7.5 days in 1970–86 to 37.1 days in 1987–2003. The annual length of the fire season, and the average time each fire burned, were also moderately correlated with the regional spring and summer temperature (Spearman's correlations of 0.61 and 0.55, ($p < 0.001$ and $p < 0.001$), respectively).

The greatest increase in wildfire frequency has been in the Northern Rockies, which accounts for 60% of the increase in large fires. Much of the remaining increase (18%) occurred in the Sierra Nevada, southern Cascades, and Coast Ranges of northern California and southern Oregon (“Northern California”, fig. S2). The Pacific Southwest, the Southern Rockies, the Northwest, coastal central and southern California, and the Black Hills each account for 11%, 5%, 5%, <1%, and <1%, respectively. Interestingly, the Northern Rockies and the Southwest show the same trend in wildfire frequency relative to their respective forested areas. However, the Southwest's absolute contribution to the western regional total is limited by its smaller forested area relative to higher latitudes.

Increased wildfire frequency since the mid-1980s has been concentrated between 1,680 m and 2,690 m in elevation, with the greatest increase centered around 2,130 m. Wildfire activity at these elevations has been episodic, coming in pulses during warm years, with relatively little activity in cool years, and is strongly associated with changes in Spring snowmelt timing, which in turn is sensitive to changes in temperature.

Fire activity and the timing of the spring snowmelt. As a proxy for the timing of the spring snowmelt, we use Stewart *et al.*'s dates of the center of mass of annual flow (CT) for snowmelt-dominated streamflow gauge records in western North America (32–34). The annual wildfire frequency for the region is highly correlated (inversely) with CT at gauges across the U.S. Pacific Northwest and interior West, indicating a coherent regional signal of wildfire sensitivity to snowmelt timing (Fig. 2). The negative sign of these correlations indicates that earlier snowmelt dates correspond to increased wildfire frequency. Following Stewart *et al.*, we used the first principal component (CT1) of CT at western U.S. streamflow gauges as a regional proxy for interannual variability in the arrival of the spring snowmelt (Fig. 1) (26, 32). This signal had its greatest impact on wildfire frequency

between 1,680m and 2,690m elevation (Fig. 2), with a non-linear response at these elevations to variability in snowmelt timing. Overall, 56% of wildfires and 72% of area burned in wildfires occurred in Early (i.e. lower tercile CT1) snowmelt years, while just 11% of wildfires and 4% of area burned occurred in Late (i.e. upper tercile CT1) snowmelt years.

Temperature affects summer drought, and thus flammability of live and dead fuels in forests through its effect on evapotranspiration and, at higher elevations, on snow. Additionally, warm spring and summer temperatures were strongly associated with reduced winter precipitation over much of the western U.S. (Fig. 3). The arrival of spring snowmelt in the mountains of the western U.S., represented here by CT1, is strongly associated with spring temperature (26). Average spring and summer temperatures throughout the entire region are significantly higher in Early than in Late years (Fig. 3), peaking in April. The average difference between Early and Late April mean monthly temperatures in forested areas was just over 2°C, and increased with elevation.

Snow carries over a significant portion of the winter precipitation that falls in western mountains, releasing it more gradually in late spring and early summer, providing an important contribution to spring and summer soil moisture (35). An earlier snowmelt can lead to an earlier, longer dry season, providing greater opportunities for large fires due both to the longer period in which ignitions could potentially occur, and to the greater drying of soils and vegetation. Consequently, it is not surprising that the incidence of wildfires is strongly associated with snowmelt timing.

Changes in spring and summer temperatures associated with an early spring snowmelt come in the context of a marked trend over the period of analysis. Regionally averaged spring and summer temperatures for 1987-2003 were 0.87°C higher than for 1970-1986. 1987-2003 Spring and summer temperatures were the warmest since the start of the record in 1895, with six years in the ninetieth percentile—the most for any 17 year period since the start of the record in 1895 through 2003—while only one year in the preceding 17 years ranked in the ninetieth percentile. Likewise, 73% of Early years since 1970 occurred in 1987-2003 (Fig. 1).

Spatial variability in the wildfire response to an earlier spring. Vulnerability of western U.S. forests to more frequent wildfires due to warmer temperatures is a function of the spatial distribution of forest area and the sensitivity of the local water balance to changes in the timing of spring. We measure this sensitivity using the October-to-September moisture deficit—the cumulative difference between the potential evapotranspiration due to temperature and the actual evapotranspiration constrained by available moisture—which is an important indicator of drought stress in plants (24). We use the percentage difference in the moisture deficit for Early

versus Late snowmelt years scaled by the fraction of forest cover in each grid cell to map forests' vulnerability to changes in the timing of spring (Fig. 4) (26). The Northern Rockies and Northern California display the greatest vulnerability by this measure—the same forests accounting for over three quarters of increased wildfire frequency since the mid-1980s. While the trend in temperature over the Northern Rockies increases with elevation, vulnerability in the Northern Rockies is highest around 2130m, where the greatest increase in fires has occurred. At lower elevations, the moisture deficit in Early years is increasing from a high average value (i.e., summer drought tends to be longer and more intense at lower elevations), while at higher elevations the longer dry season in Early years is still relatively short, and vegetation is somewhat buffered from the effects of higher temperatures by the available moisture.

Discussion. Robust statistical associations between wildfire and hydro-climate in western forests indicate that increased wildfire activity over recent decades reflects sub-regional responses to changes in climate. Historical wildfire observations exhibit an abrupt transition in the mid-1980s from a regime of infrequent large wildfires of short (average of one week) duration to one with much more frequent and longer-burning (five weeks) fires. This transition was marked by a shift toward unusually warm springs, longer summer dry seasons, drier vegetation (which provoked more and longer-burning large wildfires), and longer fire seasons. Reduced winter precipitation and an early spring snowmelt played a role in this shift. Increases in wildfire were particularly strong in mid-elevation forests.

The greatest absolute increase in large wildfires occurred in Northern Rockies forests. This sub-region harbors a relatively large area of mesic, middle and high elevation forest types (e.g., lodgepole pine and spruce-fir) where fire exclusion has had little impact on natural fire regimes (1, 5), but where we found an advance in spring produces a relatively large percentage increase in cumulative moisture deficit by midsummer. In contrast, changes in Northern California forests may involve both climate and land-use effects. In these forests, large percentage changes in moisture deficits were strongly associated with advances in the timing of spring, and this area also includes substantial forested area where fire exclusion, timber harvesting, and succession following mining activities have led to increased forest densities and fire risks (10, 11). Northern California forests have had substantially increased wildfire activity, with most wildfires occurring in Early years. Southwest forests, where fire exclusion has had the greatest effect on fire risks (2, 3), have also experienced increased numbers of large wildfires, but the relatively small forest area there limits the impact on the regional total, and the trend appears to be less affected by changes in the timing of Spring. Most wildfires in the

Southern Rockies and Southern California have also occurred in Early snowmelt years, but again forest area there is small relative to the Northern Rockies and Northern California. Thus, while land use history is an important factor for wildfire risks in specific forest types (e.g. some ponderosa pine and mixed conifer forests), the broad-scale increase in wildfire frequency across the western United States has been driven primarily by sensitivity of fire regimes to recent changes in climate over a relatively large area.

The overall importance of climate in wildfire activity underscores the urgency of ecological restoration and fuels management to reduce wildfire hazards to human communities and to mitigate ecological impacts of climate change in forests that have undergone substantial alterations due to past land uses. At the same time, however, large increases in wildfire driven by increased temperatures and earlier spring snowmelts in forests where land use history had little impact on fire risks indicates that ecological restoration and fuels management alone will not be sufficient to reverse current wildfire trends.

These results have important regional and global implications. Whether the changes observed in western hydro-climate and wildfire are the result of greenhouse gas-induced global warming, or only an unusual natural fluctuation, is presently unclear. Regardless of past trends, virtually all climate model projections indicate that warmer springs and summers will occur over the region in coming decades. These trends will reinforce the tendency toward early spring snowmelt (36, 37) and longer fire seasons. This will accentuate conditions favorable to the occurrence of large wildfires, amplifying the vulnerability the region has experienced since the mid-1980s. The Intergovernmental Panel on Climate Change's consensus range of 1.5C to 5.8C projected global surface temperature warming by the end of the 21st Century is considerably larger than the recent warming of less than 0.9°C observed in spring and summer during recent decades over the western region (37).

If the average length and intensity of summer drought increases in the Northern Rockies and mountains elsewhere in the western U.S., an increased frequency of large wildfires will lead to changes in forest composition and reduced tree densities, thus affecting carbon pools. Current estimates indicate that western US forests are responsible for 20-40% of total U.S. carbon sequestration (38, 39). If wildfire trends continue, at least initially this biomass burning will result in carbon release, suggesting that the forests of the western U.S. may become a source of increased atmospheric carbon dioxide rather than a sink, even under a relatively modest temperature increase scenario (38, 39). Moreover, a recent study shows that warmer, longer growing seasons lead to reduced CO₂ uptake in high elevation forests, particularly during droughts (40). Hence, the projected regional warming

and consequent increase in wildfire activity in the western U.S. is likely to magnify the threats to human communities and ecosystems, and significantly increase the management challenges in restoring forests and reducing greenhouse gas emissions.

References and Notes

1. C. Whitlock, *Nature* **432**, 28 (2004).
2. W. W. Covington, *Nature* **408**, 135 (2000).
3. C. D. Allen *et al.*, *Ecol. Appl.* **12**, 1418 (2002).
4. J. L. Pierce, G. A. Meyer, A. J. T. Jull, *Nature* **432**, 87 (2004).
5. T. Schoennagel, T. T. Veblen, W. H. Romme, *BioSci* **54**, 661 (2004).
6. M. Savage, T. W. Swetnam, *Ecol.* **71**, 2374 (1990).
7. A. J. Belsky, D. M. Blumenthal, *Cons. Biol.* **11**, 315 (1997).
8. S. J. Pyne, P. L. Andrews, R. D. Laven, *Introduction to Wildland Fire* (Wiley, New York, 1996).
9. W. W. Covington, M. M. More, *J. For.* **92**, 39(1994).
10. K.S. McKelvey *et al.*, in *Sierra Nevada Ecosystems Project: Final Report to Congress* (Univ. of California, Davis 1996), vol. 2, chap 37.
11. G. E. Gruell, *Fire in Sierra Nevada forests: A photographic interpretation of ecological change since 1849* (Mountain Press, Missoula, MT, 2001).
12. T. Schoennagel, T. T. Veblen, W.H. Romme, J. S. Sibold, E. R. Cook, *Ecol. Appl.* **15**, 2000 (2005).
13. R. C. Balling, G. A. Meyer, S. G. Wells, *Agric. For. Meteorol.* **60**, 285 (1992).
14. E. K. Heyerdahl, L. B. Brubaker, J. K. Agee, *Holocene* **12**, 597 (2002).
15. K. F. Kipfmüller, T. W. Swetnam, "Fire-Climate Interactions in the Selway-Bitterroot Wilderness Area" (*USDA Forest Service Proceedings RMRS-P-15-vol-5*, 2000).
16. T. W. Swetnam, J. L. Betancourt, *J. Clim.* **11**, 3128 (1998).
17. T. T. Veblen, T. Kitzberger, J. Donnegan, *Ecol. Appl.* **10**, 1178 (2000).
18. A. L. Westerling, T. J. Brown, A. Gershunov, D. R. Cayan, M. D. Dettinger, *Bull. Am. Meteorol. Soc.* **84**, 595 (2003).
19. T. W. Swetnam, J. L. Betancourt, *Science* **249**, 1017 (1990).
20. A. Gershunov, T. P. Barnett, *J. Clim.* **11**, 1575 (1998).
21. A. Gershunov, T. P. Barnett, D. R. Cayan, *EOS* **80**, 25 (1999).
22. A. L. Westerling, T. W. Swetnam, *EOS* **84**, 545 (2003).
23. N. L. Stephenson, *Am. Nat.* **135**, 649(1990).
24. N. L. Stephenson, *J. Biogeog.* **25**, 855 (1998).
25. T.W. Swetnam, *Science* **262**, 885 (1993).

26. Materials and methods are available as supporting material on *Science Online*.
27. K. E. Mitchell et al, *J. Geophys. Res.*, **109**, D07S90 (2004).
28. E. P. Maurer, A. W. Wood, J. C. Adam, D. P. Lettenmaier, B. Nijssen, *J. Clim.* **15** (2002).
29. A. F. Hamlet, D. P. Lettenmaier, *J. Hydromet.* **6**, 330 (2005).
30. NCDC, "Time Bias Corrected Divisional Temperature-Precipitation-Drought Index" (Documentation for dataset TD-9640. Available from DBMB, NCDC, NOAA, Federal Building, 37 Battery Park Ave. Asheville, NC 28801-2733, 1994).
31. X. Liang, D. P. Lettenmaier, E. F. Wood, S. J. Burges, *J. Geophys. Res.* **99**, D7 (1994).
32. I. T. Stewart, D. R. Cayan, M. D. Dettinger, *J. Clim.* **18**, 1136 (2005).
33. D. R. Cayan, S. A. Kammerdiener, M. D. Dettinger, J. M. Caprio, D. H. Peterson, *Bull. Amer. Meteor. Soc.* **82**, 399 (2001).
34. J.R. Slack, J. M. Landwehr, "Hydro-Climatic Data Network (HCDN): A U.S. Geological Survey streamflow data set for the United States for the study of climate variations, 1874–1988" (*U.S. Geological Survey Open-File Rep.* 92-129 1992).
35. J. Sheffield, G. Goteti, F. H. Wen, E. F. Wood, *J. Geophys. Res.* **109**, D24108 (2004).
36. National Assessment Synthesis Team, *Climate Change Impacts on the United States: The Potential Consequences of Climate Variability and Change* (US GCRP, Washington DC, 2000).
37. J. T. Houghton et al, Eds., *IPCC Climate Change 2001: The Scientific Basis* (Cambridge Univ. Press, Cambridge, United Kingdom and New York, NY, USA, 2001).
38. S. W. Pacala et al., *Science*, **292**, 2316 (2001).
39. D. Schimel, B. H. Braswell, in *Global Change and Mountain Regions: An overview of Current Knowledge*, U.M. Huber, H. K. M. Bugmann, M. A. Reasoner, Eds. (Dordrecht: Springer 2005), *Advances in Global Change Research Vol 23*.
40. W. Sacks, D. Schimel, R. Monson, *Oecologia*, in review (2006).
41. We thank M. Dettinger and D. Schimel for help. This work was supported by grants from the National Oceanographic and Atmospheric Administration's Office of Global Programs, the National Fire Plan via the United States Forest Service's Southern Research Station, and the California Energy Commission.

Supporting Online Material

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Materials and Methods

Figs. S1 to S3

References

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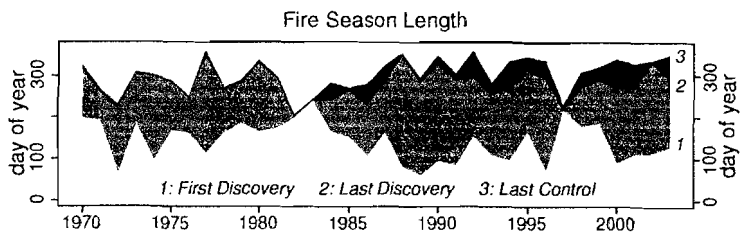
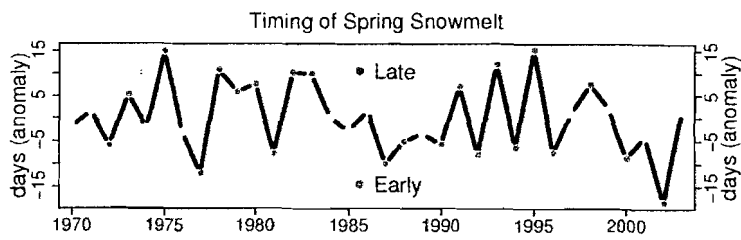
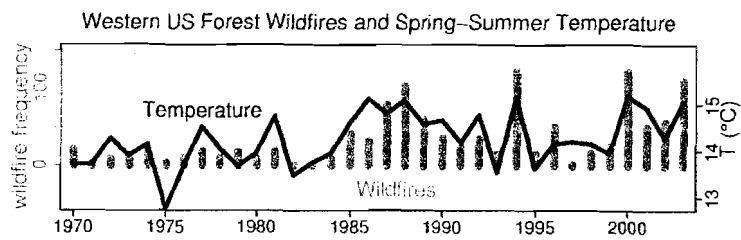
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Fig. 1. (top) Annual frequency of large (> 400 ha) western U.S. forest wildfires (bars) and mean March through August temperature for the western US (line) (26, 30). Spearman's rank correlation between the two series is 0.76 ($p < 0.001$). Wilcoxon test for change in mean large forest fire frequency after 1987 was highly significant ($W = 42$ ($p < 0.001$)). **(middle)** 1st principle component of center timing of streamflow in snowmelt dominated streams (line). Low (pink shading), middle (no shading) and high (light blue shading) tercile values indicate Early, Mid, and Late timing of spring snowmelt. **(bottom)** Annual time between first and last large fire ignition, and last large fire control.

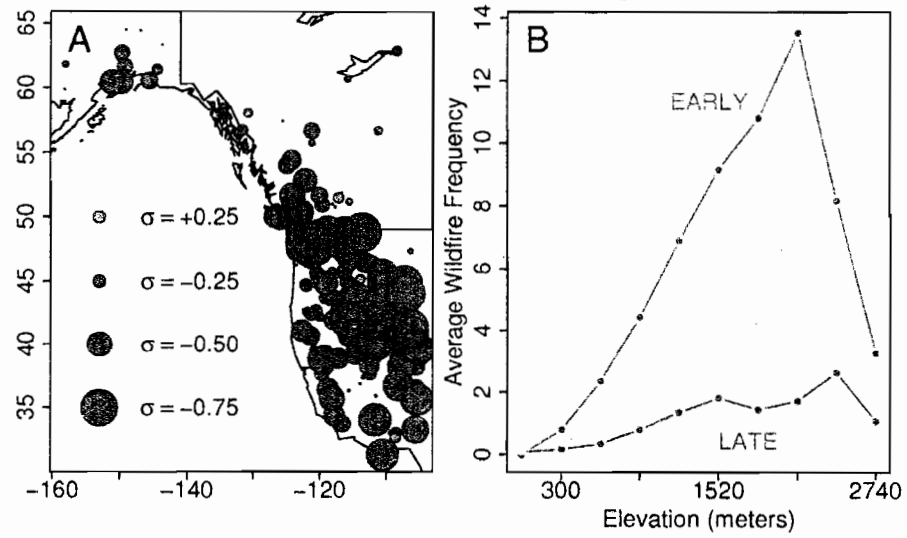
Fig. 2. (A) Pearson's rank correlation between annual western U.S. large (> 400 ha) forest wildfire frequency and streamflow center timing. **(B)** Average frequency of western US forest wildfire by elevation and Early, Mid and Late snowmelt years 1970–2002 (see Fig. 1, middle panel and legend, for a definition of Early, Mid and Late snowmelt years).

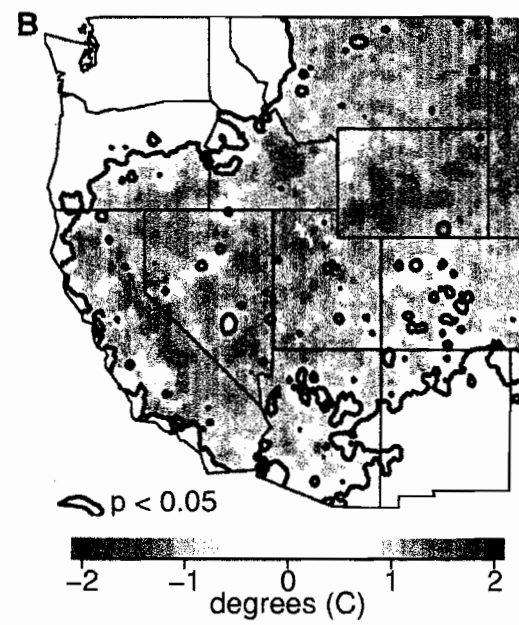
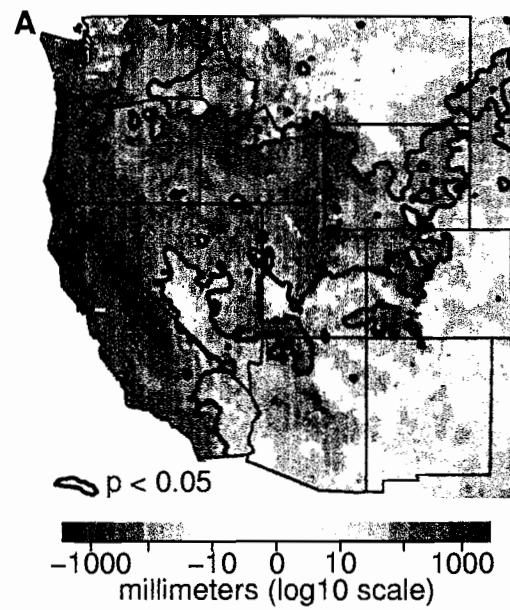
Fig. 3. Average difference between Early and Late snowmelt years' October-through-May average precipitation (**left**) and March-through-August average temperature (**right**). Contours enclose regions where a t-test for the difference in mean between 11 Early and 11 Late years was significant ($p < 0.05$). The null hypothesis that October-through-May precipitation is normally distributed could not be rejected using the Shapiro-Wilk test for normality ($p > 0.05$ for over 95% of 24170 grid cells, $n = 49$ for precipitation; $p > 0.05$ for over 95% of 24170 grid cells, $n = 50$ for temperature). (see Fig. 1, middle panel and legend, for a definition of Early, Mid and Late snowmelt years).

Fig. 4. Index of forest vulnerability to changes in the timing of spring: the percentage difference in Early versus Late snowmelt years' cumulative October-to-August moisture deficit at each grid point, scaled by the forest-type vegetation fraction at each grid point, for 1970–1999 (26). (See also fig. S3 for a map of forest vulnerability for 1970–2003 over a smaller spatial domain.) (see Fig. 1, middle panel and legend, for a definition of Early, Mid and Late snowmelt years).

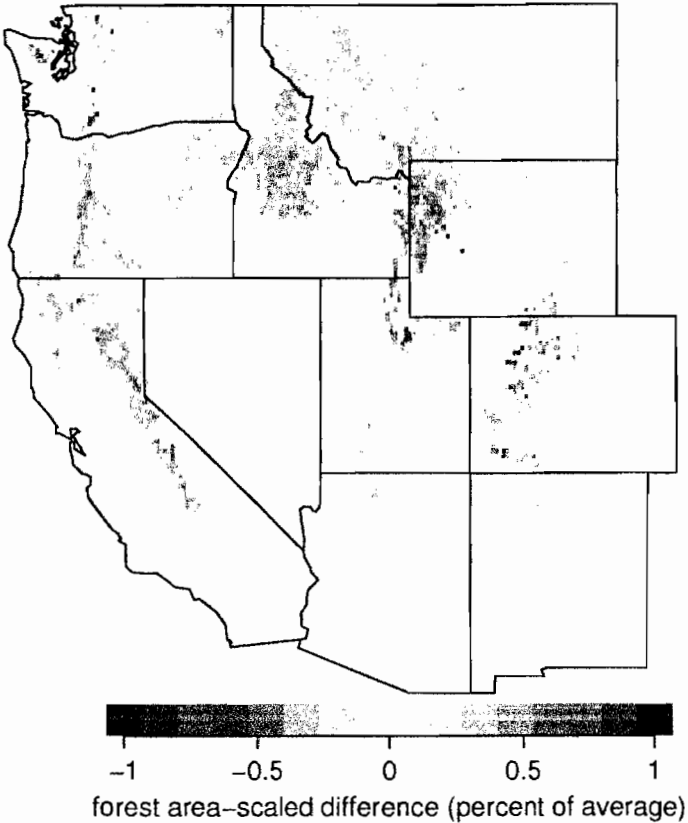


Forest Wildfire and the Timing of the Spring Snowmelt





Forest Vulnerability: Early – Late Moisture Deficit



Post-Wildfire Logging Hinders Regeneration and Increases Fire Risk

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Recent increases in wildfire activity in the United States have intensified controversies surrounding the management of public forests after large fires (1). The view that postfire (salvage) logging diminishes fire risk via fuel reduction, and that forests will not adequately regenerate without intervention that includes logging and planting, is widely held and commonly cited (2, 3). An alternative view maintains that postfire logging is detrimental to long-term forest development, wildlife habitat and other ecosystem functions (1). Scientific data directly informing this debate are lacking.

Here we present data from a study of early conifer regeneration and fuel loads following the 2002 Biscuit Fire, Oregon, USA, with and without postfire logging. Because of the fire's size (~200,000 hectares), historic reforestation difficulties in the region (4), and an ambitious postfire logging proposal, the Biscuit Fire has become a national icon of postfire management issues. We used a spatially nested design of logged and unlogged plots replicated across the fire area and sampled before (2004) and after (2005) logging (5).

Natural conifer regeneration on sites that experienced high-severity fire was variable but generally abundant, with a median stocking density of 767 seedlings per hectare, primarily of Douglas-fir (*Pseudotsuga menziesii*) (Fig. 1A). Such density exceeds regional standards for fully stocked sites, suggesting that active reforestation efforts may be unnecessary. Postfire logging subsequently reduced regeneration by 71%, to 224 seedlings per hectare (Fig. 1A), due to soil disturbance and physical burial by woody material during logging operations. Thus, if postfire logging is conducted in part to facilitate reforestation, replanting could result in no net gain in early conifer establishment.

Postfire logging significantly increased both fine and coarse downed woody fuel loads (Fig. 1B). This pulse was comprised of unmerchantable material (e.g., branches), and far exceeded expectations for postfire logging-generated fuel loads (5, 6). In terms of short-term fire risk, a reburn in logged stands would likely exhibit elevated rates of fire spread, fireline intensity and soil heating impacts (7).

Postfire logging alone was notably incongruent with fuel reduction goals. Fuel reduction treatments (prescribed burning or mechanical removal) are frequently intended following postfire logging, including in the Biscuit plan, but resources are often not allocated to complete them (8). Our study underscores that, after logging, mitigation of short-term fire risk is not possible without subsequent fuel reduction treatments. However, implementing these treatments is also problematic. Mechanical removal is generally precluded by its expense, leaving prescribed burning as the most feasible method. This will result in additional seedling mortality and potentially severe soil impacts due to long duration combustion of logging-generated fuel loads. Therefore, the lowest fire risk strategy may be to leave dead trees standing as long as possible (where they are less available to surface flames), allowing for aerial decay and slow, episodic input to surface fuel loads over decades.

Our data show that postfire logging, by removing naturally seeded conifers and increasing surface fuel loads, can be counterproductive to goals of forest regeneration and fuel reduction. In addition, forest regeneration is not necessarily in crisis across all burned forest landscapes. The results presented here suggest that postfire logging may conflict with ecosystem recovery goals.

References and Notes

1. D. B. Lindenmayer *et al.*, *Science* 303, 1303 (2004).
2. U.S. House Committee on Resources, *Forest Recovery Bill Hearing Press Release* (November 9, 2005).
3. J. Sessions, P. Bettinger, R. Buckman, M. Newton, J. Hamann, *J. For.* 102, 38 (2004).
4. S. D. Tesch, S. D. Hobbs, *W. J. Appl. For.* 4, 89 (1989).
5. Materials and methods are available as supporting material on *Science Online*.
6. Timber decay associated with delays in postfire logging was anticipated to exacerbate the observed pulse of surface fuel. However, our data indicate that delay was responsible for ~10% of woody fuel present after logging.

7. J. K. Agee, *Fire Ecology of Pacific Northwest Forests* (Island Press, Washington, DC, 1993).
8. R. W. Gorte, "Forest Fires and Forest Health" *Congressional Research Service* (Publication 95-511, 1996).
9. This work was supported by the Joint Fire Science Program and DOE grant DE-FG02-04ER63917. We thank field technicians and the Siskiyou National Forest.

Supporting Online Material

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Materials and Methods

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Fig. 1. Natural conifer regeneration (**A**) and surface woody fuel loads (**B**) before and after postfire logging of the Biscuit Fire, Oregon, USA. (**A**) Regeneration was abundant following fire. Postfire logging significantly reduced seedling densities ($P < 0.01$, Wilcoxon signed rank test) from 767 seedlings ha^{-1} to 224 seedlings ha^{-1} . (**B**) Postfire logging significantly increased downed fine ($P < 0.01$) and coarse ($P < 0.05$) woody fuel loads (Mg ha^{-1}) relative to burn-only by Wilcoxon signed rank test. To provide context, fuel data from unburned stands are shown as reference for pre-fire conditions (fuel loads in burn-logged stands were at or well above pre-fire levels). Graphs of seedling densities and fine (≤ 7.62) and coarse (> 7.62) surface woody fuels are medians \pm SE; $n = 8$ stands for no burn, $n = 9$ for burn-only and burn-logged (5).

